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Lloyd D. Tripp, Jr. & William B. Albery, Ph.D.

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G-induced loss of consciousness (GLOC), first experienced at least 65 years ago, is still killing pilots. Second only to spatial disorientation as the number one human factors problem facing the Tactical Air Force, GLOC remains a killer of both Air Force and Navy pilots. Various loss-of-consciousness research efforts in the Air Force and Navy have been initiated, but no loss-of-consciousness monitoring system (LOCOMS) has been developed for integration into modern fighter aircraft. One of the development problems is that such a LOCOMS should be invisible to the pilot and not require the donning of electrodes or special sensors that require the attention of the pilot, who will have other priorities to attend to. Taking advantage of technology originally developed for the hospital environment, the Harry G. Armstrong Aerospace Medical Research Labor- atory at Wright-Patterson AFB has developed an integrated arterial oxygen saturation monitor oxygen mask system that monitors the % SaO_2, pulse rate and pulse waveform of the pilot, even under 9 G_z. This paper describes the development and evaluation of the smart mask.

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Development of an Oxygen Mask Integrated Arterial Oxygen Saturation (SaO_2) Monitoring System for Pilot Protection in Advanced Fighter Aircraft

SSgt Lloyd D. Tripp
William B. Albery, Ph.D.
Harry G. Armstrong Aerospace Medical Research Laboratory
Biodynamics & Bioengineering Division
Acceleration Effects Branch
Wright-Patterson AFB, OH 45433-6573

ABSTRACT: G-induced loss of consciousness (GLOC), first experienced at least 65 years ago, is still killing pilots. Second only to spatial disorientation as the number one human factors problem facing the Tactical Air Force, GLOC remains a killer of both Air Force and Navy pilots. Various loss-of-consciousness research efforts in the Air Force and Navy have been initiated, but no loss-of-consciousness monitoring system (LOCOMS) has been developed for integration into modern fighter aircraft. One of the development problems is that such a LOCOMS should be invisible to the pilot and not require the donning of electrodes or special sensors that require the attention of the pilot, who will have other priorities to attend to. Taking advantage of technology originally developed for the hospital environment, the Harry G. Armstrong Aerospace Medical Research Laboratory at Wright-Patterson AFB has developed an integrated arterial oxygen saturation monitor oxygen mask system that monitors the % SaO_2, pulse rate and pulse waveform of the pilot, even under 9 G_z. This paper describes the development and evaluation of the smart mask.

METHODS AND MATERIALS: The smart mask concept incorporates current off-the-shelf technology of the Nellcor pulse oximeter with the standard issue 12-P oxygen mask. The nose bridge of an O_2 mask was instrumented with two Nellcor D-25 Oxisensors wired in parallel and held in place by clear silicone rubber (Figure 1). The Oxisensor interfaces with the Nellcor-200 signal processing unit. This unit provides percent SaO_2, pulse rate and pulse waveform information in either an analog or digital output format. The processed signals from the Nellcor-200 were patched through the sliprings of the Dynamic Environment Simulator (DES), the AAMRL human centrifuge (Figure 2), to a PDP-11 computer and back to a Gould six channel stripchart recorder. The eight subjects were Air Force personnel, mean age 27. Each subject wore the CSU 13/P anti G-suit. The smart mask was evaluated on each subject under two different G exposures. The first evaluation of the mask involved taking each subject to his relaxed, protected G tolerance. This was done via the Crosbie (1982) technique wherein the subject tracks his peripheral vision on a semi-circular light bar as he experiences increasing 0.5G levels, starting at 3.5Gz. Each subject progressed from 3.5Gz-30 second plateaus at 0.5G increments until he lost peripheral vision into a 60° cone defined by the light bar. Anti G-suit pressure, EKG, light bar position, pulse waveform, % SaO_2, and G_z Level were recorded. The second evaluation involved the subject "flying" a simulated aerial combat maneuver (SACM) while straining. The 120 second SACM contains two 7G peaks (Figure 3). The hose on the smart mask was not connected to an oxygen supply; subjects breathed ambient air through the unattached hose. A simulated ACES II, F-16 like seat with a 30° seat back angle was used in the study.

PRINCIPLE OF OPERATION: The Nellcor pulse oximeter is a combination of two technologies, oximetry and photoplethysmography, first introduced by Yoshiya et al. (1980). The Nellcor pulse oximeter integrates these two technologies by means of solid-state electronics to provide a continuous monitor of arterial oxygenation. Arterial oxygen saturation measurements obtained with this non-invasive device are in such close agreement with those determined by an in-vitro oximeter that the pulse oximeter could replace invasive arterial sampling as a means of monitoring arterial oxygen saturation and can therefore eliminate the time delay in detecting changes in oxygenation (Mackenzie, 1985).

The Nellcor pulse oximeter compares favarably with the Hewlett-Packard ear oximeter in measuring oxygen saturation within the range of 70 to 100 % in healthy volunteers. Its accuracy was 3% (95% confidence limits). This pulse oximeter also correlated with the Instrumentation Laboratory IL282 CO-Oximeter to within 2%, a result that is in agreement with the report of Yelderman and New (1983).

Pulse oximetry functions by positioning any pulsating vascular bed between a two-wavelength light source and detector (Figure 4). The nasal septal anterior enthmoid artery, supplied by the internal carotid, is a good vascular bed to monitor in a pilot because it characterizes the efficiency of the internal carotid in supplying the brain with blood and oxygen and, it is a natural inter-

face between the O_2 mask and the pilot's face. The pulsating arterial bed, by expanding and relaxing, modulates the amount of light passing through the tissue. A measurement taken in the absence of a pulse is compared with a measurement taken in the presence of a pulse, thus correcting for factors such as venous blood and other tissue. Two wavelengths are required to calculate the oxygen saturation of arterial blood. The ratio of the absorptions will give the percent hemoglobin saturation.

The final component necessary for the development of a useful monitor of arterial oxygen satruation came from the field of solid-state electronics with the introduction of high-intensity light-emitting diodes (LEDs) and the programmable microprocessor. In contrast to incandescent light, they emit a constant wavelength throughout their life, so that once calibrated they never need recalibration. Finally, since LEDs generate light of the desired wavelength, complex filtering systems do not have to be used, as with the ear oximeter. The LEDs provide monochromatic light, which is then directed through the pulsatile arterial bed to be differentially absorbed by hemoglobin. The microprocessor-based sensing circuitry measures the differential absorption of this light and computes the oxygen saturation in real time thus providing continuous monitoring of arterial oxygenation (Mackenzie, 1985).

RESULTS: The smart mask successfully tracked % SaO_2 in all eight subjects under SACM conditions; one subject wore the mask at $9G_z$ for 15 seconds. The average % SaO_2 recorded for six subjects during the SACM is shown in Figure 5. Percent SaO_2 dropped off significantly subsequent to 7G peaks. The mask tracked % SaO_2 and the pulse waveform during a 9G exposure, as well.

DISCUSSION: The smart oxygen mask offers promise as a near-term LOCOMS that can be incorporated into high performance aircraft. Because the Oxysensors can be integrated into the nose bridge of the standard 12-P oxygen mask, the pilot is unaware the system is monitoring his vital signs. The sensor leads can be incorporated into the standard microphone jack which the pilot plugs in for communications. Loss of a pulse and a subsequent drop in the % SaO_2 can be used to trigger a LOCOM system.

Percent arterial oxygen saturation as a function of +Gx exposure was monitored 25 years ago by researchers at the Mayo Clinic (Nolan, Marshall, Cronin, Sutterer, Wood, 1963). Decreases in arterial oxygen saturation which occur as a function of increasing G point up the susceptibility of lung function to changes in the force environment (Barr, 1962). Nolan et al. (1963) found that ear oximetry accurately tracked cuvette oximetry of blood being withdrawn continuously from the radial artery during 3 minute exposures to accelerations ranging from 2.1 to 5.4 G_z while breathing air (Figure 6). Deviations from normal O_2 delivery are usually the result of changes in 1) the amount of circulating hemoglobin, 2) the saturation of the hemoglobin with oxygen and 3) cardiac output (New, 1985). When a subject reaches $+4G_z$, there is a dramatic drop in end-diastolic volume, stroke volume and cardiac output as evidenced using echocardiography (Jennings, et al. 1985) and x-rays (Lindberg et al. 1969). The drop in cardiac volume and the collapse of the pulmonary aveoli during +Gz acceleration are the two primary consertive agents associated with arterial desaturation. The atelectatic effect seen in the lungs can be increased further with the use of both the anti G-suit and breathing 100% oxygen. The anti G-suit forces the diaphragm up into the thoracic cavity preventing ventilation of the alveoli to take place. When 100% O_2 is breathed before exposure to acceleration a condition exists during acceleration where the trapped gas in the alveoli will be absorbed very rapidly causing the atelectasis to occur (Dhenin, 1978). Vanderberg, Nolan, Reed & Wood, (1968) found that G-induced arterial desaturation was due to arterial-venous shunting in independent regions of the lungs.

Arterial oxygen saturation data were also recorded on ten subjects who voluntarily lost consciousness on the USAF School of Aerospace Medicine centrifuge at Brooks AFB, TX in Sep 87. These data are currently being analyzed. The Nellcor pulse oximeter accurately tracked the loss of pulse and, thus, loss of consciousness on each of these subjects. These subjects were exposed to high onset G (6G/sec) and wore a nose bridge bandage containing the Oxysensor rather than the smart mask.

Future development of the smart mask will include modifications of the pulse oximeter hardware and software for the cockpit environment, sensor array development, evaluation of the smart mask while breathing oxygen and the effect of sweat, head motion and straining on the system. Flight testing of the system is recommended.

CONCLUSION: A smart O_2 mask has been developed at the Harry G. Armstrong Aerospace Medical Research Laboratory at W-PAFB which accurately tracks the vital signs of its wearer. Because the sensors are integrated in the nose bridge of the standard 12-P oxygen mask and the sensor leads can be incorporated

into the microphone leads and jack coming from the mask, the system is completely blind to the pilot. The nasal sensor consists of two light-emitting diodes and photocell mounted in adhesive tape, allowing direct, nonslip mounting on skin; it does not require arterialized blood for operation. Instead, it uses two wavelengths of light at 660 and 940 nm and an integrated micorprocessor-based computer program to measure arteriolar blood pulsations. The pulsatile flow creates a transient change in the light path, modifying the amount of light received by the photocell. Thus, the oximeter combines measurement of the different light transmission characteristics of oxyhemoglobin and deoxyhemoglobin with the arterial pulse detection principle used by plethysmographs to compute arterial oxygen saturation. The device compares accurately with blood cuvette and other methods of measuring SaO_2.

Heart rate, pulse waveform and percent arterial oxygen saturation at the eye-brain level of the pilot can now be monitored safely and accurately. The smart mask is a promising loss of consciousness monitoring system and can be used as one "juror" in a suite of LOCOMS devices which could include head/helmet position sensing, eye blink monitoring, hands-on-stick and throttle, superficial head artery pulse sensors, superficial EEG electrode/sensors and monitoring of the G status of the aircraft. The smart mask has application for flight training and other environments including mining and firefighting.

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BIOGRAPHIES:

Lloyd Tripp is an Aeromedical Technician in the Acceleration Effects Branch, Biodynamics and Bioengineering Division of the Armstrong Aerospace Medical Research Laboratory, Wright-Patterson AFB, OH. He has an Associate Degree in Health Sciences from the Community College of the Air Force and is currently enrolled in the Human Factors Engineering program at Wright State University. He has co-authored several papers dealing with increasing man's tolerance to +Gz acceleration and holds a patent for an anti-ballooning anti-G suit. He has also developed a negative Gz acceleration protection suit.

Dr Albery is an electronics engineer in the Acceleration Effects Branch, Biodynamics and Bioengineering Division of the Armstrong Aerospace Medical Research Laboratory, Wright-Patterson AFB, OH. He received a B.S. degree in Systems Engineering from Wright State University in 1971 his M.S. degree in Biomedical Engineering from Ohio State University in 1976, and his Ph.D. in Biomedical Sciences at Wright State University in 1987. His areas of expertise are high +Gz onset accelerations, performance and workload research and flight simulation.

FIGURE 1

MODIFIED 12-P OXYGEN MASK

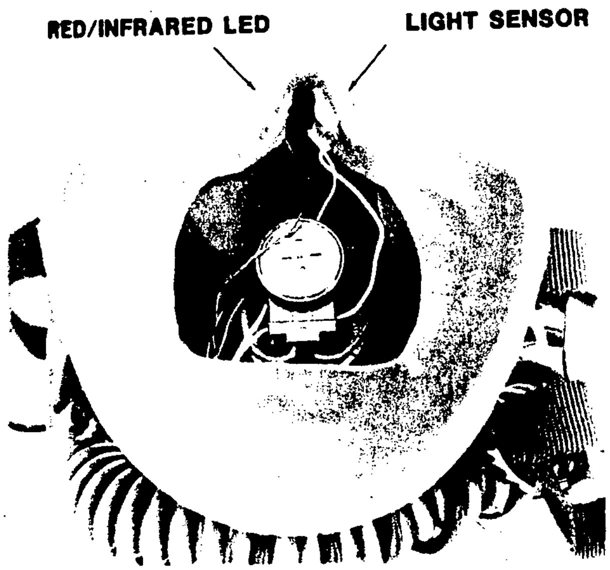

FIGURE 2

DYNAMIC ENVIRONMENT SIMULATOR (DES)

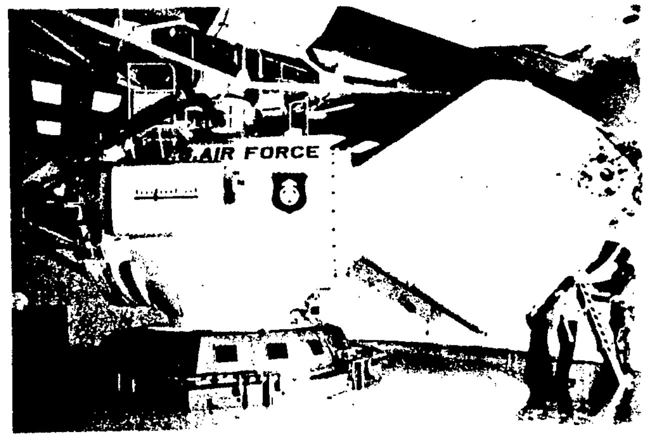

FIGURE 3

SIMULATED AERIAL COMBAT MANEUVER (SACM)

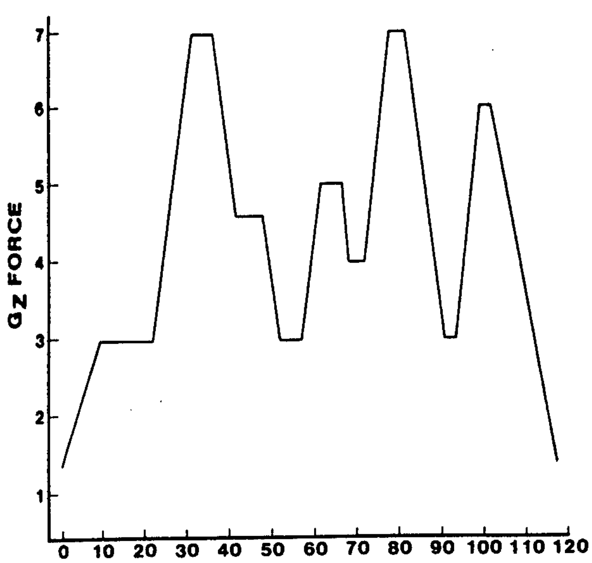

FIGURE 4

PRINCIPLE OF OPERATION

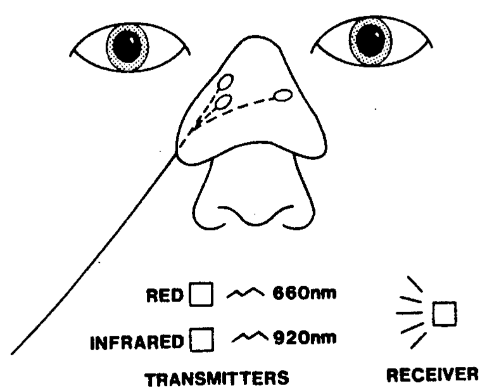

FIGURE 5

MEANS ACROSS SUBJECTS

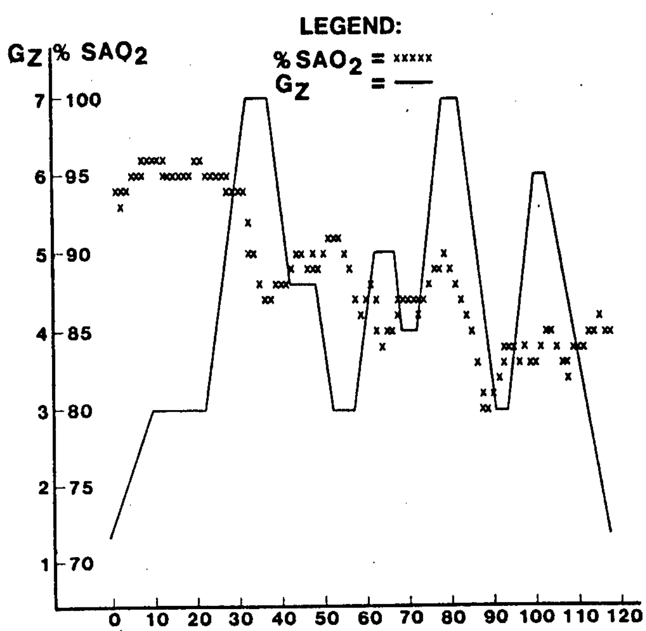

FIGURE 6